

## Method for making artificial layered high-T<sub>c</sub> superconductors.

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### Abstract

This is a method for making layered structures of artificial high-T<sub>c</sub> superconductor compounds by which on top of a seed crystal (7) having a lattice structure matching the lattice structure of the superconductor compound to be made, oxide layers (4, 5, 6) of all constituent components are epitaxially grown in a predetermined sequence so as to create a sandwich structure not found in natural crystals. The epitaxial deposition of the constituent components is performed in a reaction chamber having evaporation facilities, inlets for metal-organic gases, and inlets for background gases including oxygen.

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## Description

### METHOD FOR MAKING ARTIFICIAL LAYERED HIGH-T<sub>c</sub> SUPERCONDUCTORS

This invention relates to the manufacture of artificial high-T<sub>c</sub> superconductors having a layered structure by means of epitaxial growth. For the purposes of the following description, high-T<sub>c</sub> superconductors shall mean those materials having a transition temperature above 30 K.

Superconductivity is usually defined as the complete loss of electrical resistance of a material at a well-defined temperature. It is known to occur in many materials: About a quarter of the elements and over 1000 alloys and components have been found to be superconductors. Superconductivity is considered a property of the metallic state of the material, in that all known superconductors are metallic under the conditions that cause them to superconduct. A few normally non-metallic materials, for example, become superconductive under very high pressure, the pressure converting them to metals before they become superconductors.

Superconductors are very attractive for the generation and energy-saving transport of electrical power over long distances, as materials for forming the coils of strong magnets for use in plasma and nuclear physics, in nuclear resonance medical diagnosis, and in connection with the magnetic levitation of fast trains. Power generation by thermonuclear fusion, for example, will require very large magnetic fields which can only be provided by superconducting magnets. Certainly, superconductors will also find application in computers and high-speed signal processing and data communication.

J.G. Bednorz and K.A. Müller in their paper "Possible High T<sub>c</sub> Superconductivity in the Ba-La-Cu-O

System" Z. Phys. B - Condensed Matter 64, 189-193 (1986), have described a new class of superconducting materials with a transition temperature in the neighbourhood of 35 K. It has meanwhile been confirmed that one precondition for the existence of high-T<sub>c</sub> superconductivity in composite metallic oxides is the layered structure of the material. (In the literature, the layered structure is often referred to as being of the "K<sub>2</sub>NiF<sub>4</sub> type" because the structure was first observed in this material.)

This structure is in particular present in oxides of the general composition RE<sub>2</sub>TM.O<sub>4</sub>, wherein RE stands for the rare earths (lanthanides) and TM stands for the so-called transition metals. In the compounds in question, the RE portion may be partially substituted by one member of the alkaline earth group of metals, or by a combination of the members of this alkaline earth group. The oxygen content is generally at a deficit.

For example, one such compound that meets the description given above is lanthanum copper oxide La<sub>2</sub>CuO<sub>4</sub> in which the lanthanum -which belongs to the IIIB group of elements- is in part substituted by one member of the neighboring IIA group of elements, viz. by one of the alkaline earth metals (or by a combination of the members of the IIA group), e.g., by barium. Also, the oxygen content of the compound is incomplete such that the compound will have the general composition of La<sub>2-x</sub>Ba<sub>x</sub>CuO<sub>4-y</sub>, wherein x The present invention, too, is directed to compounds having a layer-type structure. The thickness of the layers involved has been determined to be on the order of tenths of a nanometer (10 m), i.e. the layers are mono-molecular. However, a coupling between the layers is of importance. A theoretical way of fabricating molecular sandwich structures involves the generation and subsequent etching of natural crystals of the desired composition and having a perovskitic structure, although only a very limited parameter range (chemical elements, stoichiometry) is available.

It is an object of the invention to propose a new method for making layered superconductors through growth by mono-layer epitaxy, including a variation of their stacking in order to obtain optimal conditions. The advantage of mono-layer epitaxy is the considerably greater freedom in the selection of the materials (chemical elements as well as compounds) and in the sequencing of the layers than is possible when starting from natural crystals having a perovskitic structure.

Epitaxy per se is well known, cf. for example, I. Brodie and J.J. Murray, The Physics of Microfabrication, Plenum Press, New York and London, 1982, pp. 16 ff. The term epitaxy describes a deposition process whereby a single-crystal material is applied to a substrate having the same crystal orientation. In order for the depositing material to atomically interface with the substrate surface, two important conditions must be met: Firstly, the substrate surface must present to the depositing material a suitable number of nucleation sites where deposited atoms give up some energy and bond to the surface atoms; and secondly, the lattice match of the surface relative to the depositing material must be a maximum.

The epitaxy process is performed in a reactor chamber, usually at elevated temperatures and in an atmosphere with specially controlled pressure, or in vacuo. Depending on the mechanism by which the depositing material is replenished in the reactor chamber, one distinguishes between three types of epitaxy processes, viz. vapor-phase epitaxy (VPE), liquid-phase epitaxy (LPE), and molecular beam epitaxy (MBE).

In the vapor-phase epitaxy process, a gas stream containing the material to be deposited is caused to flow over the heated substrates. The growth rate of the epitaxial layer can be made a function of the concentration in the gas stream of the material to be deposited.

One example of a prior reference to vapor-phase epitaxy is US-A-4,058,430 which discloses a method for growing highly oriented compound thin films on a substrate by subjecting the substrate to the vapor of a first single element which can react with the substrate surface at a temperature sufficiently high for the reaction to occur, to form a single atomic layer of the first single element on the surface, and then subjecting the thus formed new surface to the vapor of a second single element which can react with the first single element at a temperature sufficiently high for the reaction to occur, so as to form a single atomic layer of the second single element on the surface of the first single element. This procedure is repeated until the compound film reaches the desired thickness.

In the liquid-phase epitaxy process, the material to be deposited is retained in a solution holder at elevated temperature, and is brought in contact with the substrate as holder and substrate are mutually displaced. With a plurality of solution holders in a row, it is possible to deposit multilayers of different materials onto

the same substrate.

Liquid-phase epitaxy was, for example, described by H. Nelson, "Epitaxial growth from the liquid state and its applications to the fabrication of tunnel and laser diodes", RCA Rev. 24 (1963) p.603. Nelson used a tipping system, where the substrate and the epitaxial solution are placed at opposite ends of a graphite boat which in turn is arranged inside a growth tube containing a high-purity atmosphere. The tube is situated in a furnace that can be tipped to elevate either end of the boat. The solution used consists of gallium and gallium arsenide in such amounts that saturation occurs at the growth temperature.

The third type of epitaxy process, the molecular beam epitaxy, achieves crystal growth in an ultra-high vacuum environment through the reaction of multiple molecular beams with the heated substrate. The molecular beam sources each consist of a furnace containing one of the constituent elements of the deposit in a crucible. The furnaces are arranged so that the central portion of the beam flux distribution intersects the substrate. Shutters arranged on each of the furnaces permit the controlled initiation or cessation of the respective beam fluxes.

One example for the great volume of literature on molecular beam epitaxy is K. Ploog, "Molecular Beam Epitaxy of III-IV compounds, Crystals: Growth, Properties and Applications, ed. L.F. Boschke, Heidelberg, Springer-Verlag (1979).

For the purposes of the present invention, advanced techniques of the three basic epitaxy processes are employed, such as metal-organic vapor-phase epitaxy (MOVPE) or chemical beam epitaxy (CBE), to grow very abrupt interfaces and, at the same time, allow the deposited layers to be very thin through precise control of the growth parameters.

The paper "Single Crystal Superconducting Y1Ba2Cu3O7-x Oxide Films By Molecular Beam Epitaxy" by J. Kwo, M. Hong, R.M. Fleming, T.C. Hsieh, S.H. Liou, and B.A. Davidson, published in Conference Proceedings "Novel Mechanisms of Superconductivity" June 22 through 26, 1987, Berkely, CA., describes a method for preparing single-crystal Y1Ba2Cu3O7-x films by thermally coevaporating the constituents of the films from three separate sources simultaneously onto the (100) face of SrTiO3. The films produced with this method are amorphous and have a reported thickness of about 900 nm.

Another reference dealing with "thick" films (about 1  $\mu$ m) is C. Webb et al., "Growth of high-Tc superconducting films using molecular beam epitaxy techniques", Appl. Phys. Lett. 51 (15) 1987, pp. 1191-1193. The high-Tc superconductor reported in this reference is DyBa2Cu3O7-x which has been grown onto a SrTiO3 substrate. However, in this case, as well as in the above-mentioned Kwo et al. reference, the films required oxidation at elevated temperatures as a post-anneal process in order for them to become superconducting.

The present invention is, however, not directed to such thick films but rather to the formation of mono-layer films, i.e. films comprising only one or very few molecular layers of a superconducting material. Of relevance in this connection is a paper by M.A. Tischler and S.M. Bedair, "Growth and Characterization of Compound Semiconductors by Atomic Layer Epitaxy", Journal of Crystal Growth 77 (1986) pp. 89-94. As described in this reference, growth proceeds by the sequential deposition of individual layers of atoms of the elements making up the final compound. For example, gallium arsenide is grown by first depositing an atomic layer of gallium and then an atomic layer of arsenic. The cycle is repeated until the desired thickness is achieved. The first atomic layer is chemically adsorbed at the substrate surface, any following atoms are only weakly bonded and tend to re-evaporate. This is a self-limiting mechanism which prevents the deposition of more than one monolayer at a time. The second-material atomic layer finds a fresh surface and again, one monolayer of atoms gets adsorbed to that new surface. If the operational parameters are appropriate, a chemical reaction will cause the atomic monolayers to form a monomolecular layer of the desired compound.

While in the Tischler-Bedair proposal cited above the new compound is generated from pure elements, in a proposal by H. Watanabe and A. Usui "Atomic Layer Epitaxy", Inst. Phys. Conf. Ser. No. 83: Chapter I, Paper presented at Int. Symp. GaAs and Related Compounds, Las Vegas, Nevada, 1986, the starting materials are metal halogenides or metalorganic compounds, such as GaCl and Ga(CH3)3, and arsine AsH3.

All of the references cited above, while dealing with thin film epitaxy, do not relate to the formation of the

crystallographic structure of the superconducting compound synthesized, except that, of course, some of them mention that the superconducting phase must have a layered structure of the  $K_2NiF_4$  type.

In contrast, it is an object of the present invention to propose a method for making high- $T_c$  superconductors having a predetermined crystallographic structure. This object is achieved by epitaxially growing sequences of atomic layers of the elements constituting the desired superconductor compound onto surfaces having a crystallographic structure at least similar to the structure of the compound being made. The superconductor structure finally achieved can comprise from one single monomolecular layer to a plurality of monomolecular layers which may make up a sandwich structure. The layers may be stacked in regular or non-regular sequences not possible in natural crystals. The non-regular sequence, in particular, may be grown in a fractal way. The fractals are determined mathematically.

Details of the invention will hereafter be described with respect to some examples of artificial high- $T_c$  superconductor materials, with reference to the attached drawings in which:

Fig. 1 shows the crystal lattice of strontium titanate  $SrTiO_3$ ;

Fig. 2 illustrates the crystal structure of artificial  $La_2CuTiO_6$ ;

Fig. 3 depicts the crystal structure of artificial  $La_2Cu(Al_{1/2}, Zr_{1/2})O_6$ ;

Fig. 4 shows the lattice structure of artificial  $Sr_2LaCu_2WO_9$ ;

Fig. 5 shows the crystal structure of the orthorhombic form of  $YBa_2Cu_3O_7$ ;

Fig. 6 is a schematic representation of epitaxy apparatus suited to create the artificial superconductor compounds in accordance with the invention.

One material particularly suited as a substrate in the epitaxial growth of high- $T_c$  superconductor material is strontium titanate  $SrTiO_3$ , which forms crystals like perovskite (Fig. 1). Each titanium ion 1 is octahedrally surrounded by six oxygen ions 2; the bigger strontium ions 3 being disposed in the spaces in between. At room temperature,  $SrTiO_3$  is cubic with a small unit cell, and paraelectric. At about 100 K,  $SrTiO_3$  starts to undergo a cubic-tetragonal phase transition with a non-ferroelectric phase, because this phase is more favorable energetically.

Another material suitable as a substrate is zirconium dioxide  $ZrO_2$ . This material can even be coated over polycrystalline silicon bulk material, in order to minimize any mismatches in lattice constants.

Still another promising material is zinc selenide  $Zn_{1-x}Sex$ . By varying  $x$ , the lattice constant of this compound can be adjusted within certain borders, so as to render it essentially equal to the lattice constant of the high- $T_c$  superconductor material to be grown.

Other examples of materials suitable as a substrate for the growth of high- $T_c$  superconductor materials include barium fluoride  $BaF_2$ , and II/VI compounds such as zinc telluride  $Zn_{1-x}Tex$ , cadmium selenide  $Cd_{1-x}Sex$ , and cadmium telluride  $Cd_{1-x}Tex$ .

Returning to the manufacturing of artificial high- $T_c$  superconductor materials, it has been found that one essential feature is the layered structure of the superconducting metal oxides. The monolayer epitaxy allows for the generation of such layers and for a systematic variation of the layer sequences and, most important, of the crystalline structure of those layers. Figs. 2, 3, and 4 show examples of layered perovskite high- $T_c$  superconductors that can be grown with single-valence or mixed-valence copper oxide layers separated by non-superconducting metal oxide layers.

Another essential feature of high- $T_c$  perovskite copper oxide superconductors is the antiferromagnetic character of the non-conducting (i.e. undoped) oxide at low temperatures. The antiferromagnetic behavior is characterized by a state in which neighboring spins are antiparallel, instead of parallel. Accordingly, the non-conducting copper oxide exhibits a paramagnetism with low positive susceptibility that varies with temperature.

Fig. 2 is a representation of a crystal lattice of an artificial high- $T_c$  superconductor compound manufactured in accordance with the present invention. The compound is  $La_2CuTiO_6$ . Its crystal structure is of the ABB min type and consists of a layer sequence comprising a (B) copper oxide layer 4, a (B min) titanium oxide layer 5, and interstacked (A) lanthanum oxide layers 6. The copper oxide and titanium oxide layers 4 and 5, respectively, consist of octahedra having metal atoms in their centers and shared oxygen atoms at their corners. The spaces between every four octahedra house one lanthanum atom 6 each. This crystal structure is grown on top of a  $SrTiO_3$  crystal 7 which has essentially the same lattice constant as the

desired superconductor material.

Fig.3 shows an example of an ABB min structure of  $\text{La}_2\text{Cu}(\text{Al}_{1/2}, \text{Zr}_{1/2})\text{O}_6$ . The layer sequence consists of a mixed (B min) Al/Zr oxide layer 8, a (A) lanthanum oxide layer 9 and a (B) mixed-valence Cu/Cu oxide layer 10. This lattice is grown on top of a  $\text{SrTiO}_3$  crystal 11 with an interstacked lanthanum layer 12.

While the manufacture of one-constituent oxide layers is straightforward, the creation of oxide layers of the mixed Al/Zr type requires the simultaneous presence of Al and Zr in a 1:1 relationship, preferably in the form of gaseous organic compounds of these metals. Examples for organic compounds of interest in this connection are aluminium alkoxide  $\text{Al}(\text{OCH}_3)_3$  and zirconium cyclopentadienyl  $\text{Zr}(\text{OC}_2\text{H}_5)_2$ .

Generally, the following types of metalorganic compounds may find use in connection with the present invention:

Columns=3>

Head Col 1: Type

Head Col 2: Example

Head Col 3: Name

Halogenides  $\text{YCl}_3$  Yttrium chloride

Alkyls  $(\text{CH}_3)_3\text{La}$  Methyl lanthanum

Alkoxides  $\text{Ba}(\text{OCH}_3)_2$  Methoxybarium

Acetylacetonates  $\text{Ba}[\text{OC}(\text{CH}_3):\text{CHCO}(\text{CH}_3)]_2$  Barium acetylacetonate

Cyclopentadienyls  $(\text{C}_5\text{H}_5)_2\text{Ba}$  Barium cyclopentadienyl

Carbonyls  $\text{C}_5\text{H}_5\text{Mn}(\text{CO})_3$  Manganese cyclopentadienyl Carbonyl

An example of a crystal structure of the AA min BB min type is shown in Fig.4. The superconductor material is  $\text{Sr}_2\text{LaCu}_2\text{WO}_9$ . The layer sequence consists of mixed (B)  $\text{Cu}@@@$  and (B min) W oxide layers 13 and 14, respectively, separated alternatively by (A)  $\text{Sr}_2$  and (A min) La oxide layers 15 and 16, respectively. Again, the crystal lattice rests on top of a  $\text{SrTiO}_3$  crystal 17 with an interstacked lanthanum layer 16 min.

Fig.5 shows another artificial superconductor compound in its orthorhombic form, viz.  $\text{YBa}_2\text{Cu}_3\text{O}_7$ . In contrast to the cubic perovskite structure with only corner-shared octahedra, in the compound of Fig.5, corner-sharing square pyramid copper oxide layers 18 and 19 arranged opposite each other form rhombic spaces in which first and second layers 20, 20 min of barium atoms 21 (forming barium oxide  $\text{BaO}$ ) are disposed, separated by at least one other copper oxide layer 22 consisting of ribbons of square-planar  $\text{CuO}_4$  polyhedra. Neighboring layers 18 and 19, respectively, comprising the pyramid shaped copper oxide are joined by interstacked planar layers 23 of yttrium oxide.

It has been found (T. Schneider and D. Baeriswil, Critical Temperature of High-Tc Superconductors, Zeitschrift für Physik A, -to be published) that the critical temperature  $T_c$  of superconductors of the type shown in Fig.5 is dependent on the number  $n$  of interstacked copper oxide layers,  $T_c = f(n)$ . This provides for the possibility of "engineering" the superconductor compounds so as to adapt their critical temperature to the needs of the particular circumstances by choosing the appropriate number of layers. Accordingly, in the compound shown in Fig.5, more planar  $\text{CuO}_4$  layers 22 may be added.

Having described some examples of artificial high-Tc superconductors, the description will now turn to the apparatus for growing epitaxial layers. This is basically a sophisticated extension of vacuum evaporation apparatus comprising a multichamber vessel 25 having a fast entry load-lock 26, a preparation chamber 27 and a growth chamber 28. A typical setup is illustrated in Fig.6. Vessel 25 can be pumped to ultra-high vacuum conditions (about 10 Pa) using a suitable combination of ion, cryo-, turbomolecular, diffusion, sorption and sublimation pumps 29. The use of UHV conditions enables the incorporation of high-vacuum based surface analytical and diagnostic techniques. For example, reflection high-energy electron diffraction (RHEED) apparatus 30 may be employed to examine the substrate prior to, and the actual epitaxial film during deposition. A mass spectrometer 31 may be provided for monitoring the gas composition in growth chamber 28 and for detecting possible leaks. Other surface analysis instruments, such as an Auger electron spectroscopy 32, may be placed in preparation chamber 27 to reduce contamination problems.

The monocrystalline substrate 33 is arranged on a trolley 34 which enables it to be moved between load-lock 26 and growth chamber 28, passing preparation chamber 27. Substrate 33 may be heated by a



heating coil 35. Facing substrate 33 are a number of sources 36 through 40 from which different materials can be emitted in the epitaxy process. These individually shuttered sources may encompass, for example, evaporators heated resistively or by electron beam, or sources for metals in the form of metal-organic compounds, or gas sources for performing dielectric, metal or metal oxide depositions. In addition, several gas inlets 41 through 44 are provided for introducing controlled amounts of known gases.

Substrate 33 is preferably oriented in vertical direction to facilitate the deposition of materials from the beams emitted from sources 36 through 40. To maintain a constant distance of sources 36 through 40 from substrate 33, the sources may be arranged on a remote-controlled arcuate (or straight) slider 45.

In operation, after the monocrystalline substrate 33 is placed on trolley 34 and introduced into vessel 25, load-lock 26 is closed. After pumping to UHV conditions, substrate 33 is brought into position for deposition. The appropriate one of sources 36 through 40 is placed opposite substrate 33. After substrate 33 has reached its operative temperature, the shutters of the first set of sources are opened, and/or the appropriate gas inlet(s) is operated, for a predetermined period of time. The first part of the epitaxy cycle is completed when a monoatomic or monomolecular layer of the first constituent has settled on the substrate.

The second part of the epitaxy cycle is started as soon as there is no residue left in the vacuum of the preceding source material. Then the second set of sources is activated for the appropriate period of time so as to permit the second source material to react with the first source material as determined by the stoichiometry of the materials in question.

This procedure is repeated for all individual constituents the deposit is finally to contain, and the entire cycle is repeated for each additionally desired layer of the superconductor material.

Over any other methods for the creation of chemical compounds, the monolayer epitaxy process has the advantage that it permits the formation of artificial compounds, i.e. those that do not exist in nature, on top of seed crystals having essentially the same lattice structure as the compounds desired. This is in contrast to other deposition methods by which only polycrystalline, or bulk materials can be obtained. In view of the fact that layered structure is an essential feature of all high-T<sub>c</sub> superconductors, the inventive method is of great importance in the manufacture of these superconductors.

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## Claims

1. Method for making artificial, layered high-T<sub>c</sub> superconductor compounds by monolayer epitaxy, characterized by the following steps:

- placing a monocrystalline substrate (7, 11, 17, 33) of a material from the group comprising strontium titanate SrTiO<sub>3</sub>, zirconium dioxide ZrO<sub>2</sub>, zinc telluride Zn<sub>1-x</sub>Tex, zinc selenide Zn<sub>1-x</sub>Sex, BaF<sub>2</sub>, cadmium selenide Cd<sub>1-x</sub>Sex, and cadmium telluride Cd<sub>1-x</sub>Tex, wherein  $x < 1$ , in an UHV chamber (27, 28) having a plurality of independent sources (36...40) for materials for epitaxial deposition,
- exposing said substrate (7, 11, 17, 33) in a predetermined sequence to as many different ones of said sources (36...40) of constituent materials as the superconductor compounds being made should contain,
- activating said sources (36...40) in accordance with a predetermined pattern of activity, said pattern involving
  - . data determining which particular constituent material is to be deposited at any one time;
  - . data relating to the amount and concentration of the particular constituent material to be emitted from the activated source (36...40)
  - . data relating to the period of time the exposure of said substrate (7, 11, 17, 33) to the individual constituent materials should last for one monoatomic/monomolecular layer of the particular constituent material to settle on the current substrate surface;;
  - . data relating to the operating temperature at which the exposure is to be performed, said data including information on the operating temperature of the current substrate surface, on the operating temperature of the source (36...40) of the particular constituent material, and on the reaction temperature required for the desired high-T<sub>c</sub> superconductor material to form in accordance with a particular, desired crystal structure;

- repeating the preceding steps as often as corresponds to the number of monomolecular/monoatomic layers the final superconductor compound should contain;
- cooling the resulting crystal to ambient temperature and removing it from the UHV chamber (27, 28).

2. Method in accordance with claim 1, characterized in that the epitaxial deposition of at least part of said constituent materials is made from a gas phase.

3. Method in accordance with claim 1, characterized in that said gas phase contains the metal atoms to be deposited in the form of an organic compound of the particular metal.

4. Method in accordance with claim 1, characterized in that the epitaxial deposition of said constituent materials is made from at least one molecular beam of the particular material(s).

5. Method in accordance with claim 1, characterized in that said monocrystalline substrate (7) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (6) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said strontium titanate substrate (7), that in a second epitaxial operation a layer (4) of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said lanthanum oxide monolayer (6), that in a third epitaxial operation a second monolayer (6 min) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said cuprous oxide layer (4), that in a fourth epitaxial operation a monolayer (5) of octahedral titanium dioxide  $\text{TiO}_2$  is deposited onto said second lanthanum oxide monolayer (6 min), the four individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{La}_2\text{CuTiO}_6$  crystal to be stoichiometrically correct and to assume a layered, octahedral structure of the ABB min type.

6. Method in accordance with claim 5, characterized in that said sequence of four epitaxial deposition operations is repeated as many times as the desired thickness of the resulting superconductor compound requires.

7. Method in accordance with claim 1, characterized in that said monocrystalline substrate (11) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a monomolecular layer (12) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said substrate (11), that in a second epitaxial operation a monolayer (8) of mixed aluminium oxide  $\text{Al}_2\text{O}_3$  and zirconium oxide  $\text{ZrO}_2$  is deposited onto said layer (12) of lanthanum oxide, that in a third epitaxial operation a second layer (9) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said monolayer of mixed oxides, and that in a fourth epitaxial operation octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second monolayer (9) of lanthanum oxide, the four individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{La}_2\text{Cu}(\text{Al}_{1/2}, \text{Zr}_{1/2})\text{O}_6$  crystal to be stoichiometrically correct and to assume a layered, octahedral structure of the ABB min type.

8. Method in accordance with claim 1, characterized in that said monocrystalline substrate (17) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (16 min) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said monocrystalline substrate (17), that in a second epitaxial operation a first monomolecular layer (13) of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said lanthanum oxide layer (16 min), that in a third epitaxial operation a first monomolecular layer (15) of strontium oxide  $\text{SrO}$  is deposited onto said monolayer (13) of cuprous oxide, that in a fourth epitaxial operation a first monomolecular layer (14) of tungstic oxide  $\text{WO}_3$  is deposited onto said first strontium oxide monolayer (15), that in a fifth epitaxial operation a second monomolecular layer (15 min) of strontium oxide  $\text{SrO}$  is deposited onto said monomolecular layer (14) of tungstic oxide, that in a sixth epitaxial operation a second monomolecular layer (13 min) of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second strontium oxide layer (15 min), and that in a seventh epitaxial operation a second monomolecular layer (16) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said cuprous oxide layer (13 min), the seven individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{Sr}_2\text{LaCu}_2\text{WO}_9$  crystal structure of the AA min B type.

9. Method in accordance with claim 1, characterized in that said monocrystalline substrate (33) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (23) of yttrium oxide  $\text{Y}_2\text{O}_3$  is deposited onto said monocrystalline substrate (33), that in a second epitaxial operation a first monomolecular layer (19) of pyramidal cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said yttrium oxide layer (23), that in a third epitaxial operation a first monomolecular layer (20) of barium oxide  $\text{BaO}$  is

deposited onto said monolayer (19) of cuprous oxide  $\text{Cu}_2\text{O}$ , that in a fourth epitaxial operation a layer (22) of ribbons of square planar copper oxide  $\text{CuO}_4$  polyhedra is deposited onto said barium oxide layer (20), that in a fifth epitaxial operation a second monomolecular layer (20 min ) of barium oxide  $\text{BaO}$  is deposited onto said layer (22) of copper oxide polyhedra, that in a sixth epitaxial operation a second monomolecular layer (18) of pyramidal cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second barium oxide layer (20 min ), and that in a seventh epitaxial operation a second monomolecular layer (23) of yttrium oxide is deposited onto said cuprous oxide layer (18), the seven individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature, so as to permit the nascent  $\text{YBa}_2\text{Cu}_3\text{O}_7$  crystal to be stoichiometrically correct and to assume a layered, orthorhombic structure.

10. Method in accordance with claim 5, characterized in that said first and second monolayers (23) of yttrium oxide have a square planar structure.

11. Method in accordance with claim 5, characterized in that said  $\text{YBa}_2\text{Cu}_3\text{O}_7$  crystal comprises at least two orthorhombic lattices consisting of  $\text{Ba}_2\text{Cu}_3\text{O}_5$  with an interstacked square planar yttrium oxide  $\text{Y}_2\text{O}_3$  layer (23).

12. Method in accordance with claim 5, characterized in that said cycle of seven epitaxial deposition steps is repeated as often as the desired thickness of the resulting layered structure requires.

13. Method in accordance with claim 5, characterized in that said fourth epitaxial deposition step in which a layer (22) of copper oxide  $\text{CuO}_4$  is deposited, is repeated at least once prior to continuing with the fifth step deposition so as to create a layered structure comprising more than one layer (22) of copper oxide  $\text{CuO}_4$  between consecutive layers (20, 20 min ) of barium oxide  $\text{BaO}$ .

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54 Method for making artificial layered high-T<sub>c</sub> superconductors.

57 This is a method for making layered structures of artificial high-T<sub>c</sub> superconductor compounds by which on top of a seed crystal (7) having a lattice structure matching the lattice structure of the superconductor compound to be made, oxide layers (4, 5, 6) of all constituent components are epitaxially grown in a predetermined sequence so as to create a sandwich structure not found in natural crystals. The epitaxial deposition of the constituent components is performed in a reaction chamber having evaporation facilities, inlets for metal-organic gases, and inlets for background gases including oxygen.

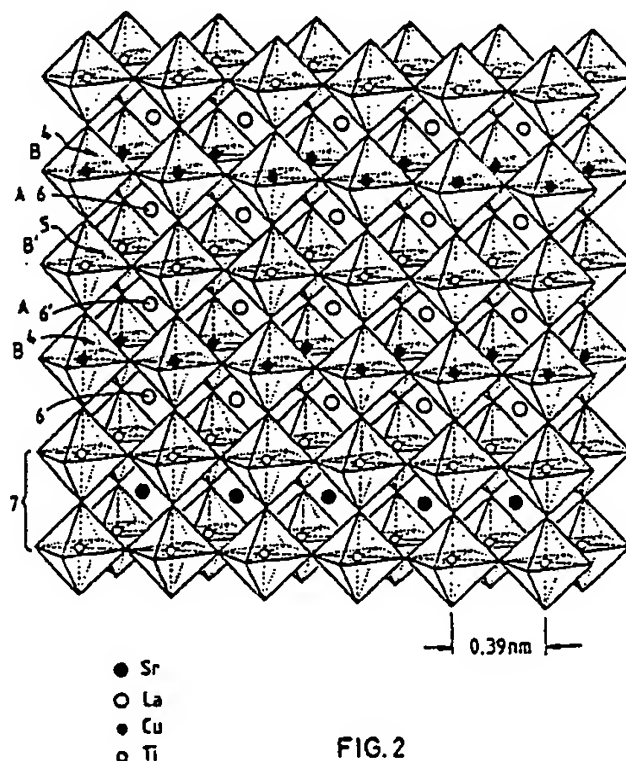


FIG. 2

METHOD FOR MAKING ARTIFICIAL LAYERED HIGH- $T_c$  SUPERCONDUCTORS

This invention relates to the manufacture of artificial high- $T_c$  superconductors having a layered structure by means of epitaxial growth. For the purposes of the following description, high- $T_c$  superconductors shall mean those materials having a transition temperature above 30 K.

Superconductivity is usually defined as the complete loss of electrical resistance of a material at a well-defined temperature. It is known to occur in many materials: About a quarter of the elements and over 1000 alloys and components have been found to be superconductors. Superconductivity is considered a property of the metallic state of the material, in that all known superconductors are metallic under the conditions that cause them to superconduct. A few normally non-metallic materials, for example, become superconductive under very high pressure, the pressure converting them to metals before they become superconductors.

Superconductors are very attractive for the generation and energy-saving transport of electrical power over long distances, as materials for forming the coils of strong magnets for use in plasma and nuclear physics, in nuclear resonance medical diagnosis, and in connection with the magnetic levitation of fast trains. Power generation by thermonuclear fusion, for example, will require very large magnetic fields which can only be provided by superconducting magnets. Certainly, superconductors will also find application in computers and high-speed signal processing and data communication.

J.G. Bednorz and K.A. Müller in their paper "Possible High  $T_c$  Superconductivity in the Ba-La-Cu-O System" Z. Phys. B - Condensed Matter 64, 189-193 (1986), have described a new class of superconducting materials with a transition temperature in the neighbourhood of 35 K. It has meanwhile been confirmed that one precondition for the existence of high- $T_c$  superconductivity in composite metallic oxides is the layered structure of the material. (In the literature, the layered structure is often referred to as being of the " $K_2NiF_4$  type" because the structure was first observed in this material.)

This structure is in particular present in oxides of the general composition  $RE_2TM.O_4$ , wherein RE stands for the rare earths (lanthanides) and TM stands for the so-called transition metals. In the compounds in question, the RE portion may be partially substituted by one member of the alkaline earth group of metals, or by a combination of the members of this alkaline earth group. The oxygen content is generally at a deficit.

For example, one such compound that meets the description given above is lanthanum copper oxide  $La_2CuO_4$  in which the lanthanum -which belongs to the IIIB group of elements- is in part substituted by one member of the neighboring IIA group of elements, viz. by one of the alkaline earth metals (or by a combination of the members of the IIA group), e.g., by barium. Also, the oxygen content of the compound is incomplete such that the compound will have the general composition of  $La_{2-x}Ba_xCuO_{4-y}$ , wherein  $x \leq 0.3$  and  $y < 0.5$ .

The present invention, too, is directed to compounds having a layer-type structure. The thickness of the layers involved has been determined to be on the order of tenths of a nanometer ( $10^{-10}$  m), i.e. the layers are mono-molecular. However, a coupling between the layers is of importance. A theoretical way of fabricating molecular sandwich structures involves the generation and subsequent etching of natural crystals of the desired composition and having a perovskitic structure, although only a very limited parameter range (chemical elements, stoichiometry) is available.

It is an object of the invention to propose a new method for making layered superconductors through growth by mono-layer epitaxy, including a variation of their stacking in order to obtain optimal conditions. The advantage of mono-layer epitaxy is the considerably greater freedom in the selection of the materials (chemical elements as well as compounds) and in the sequencing of the layers than is possible when starting from natural crystals having a perovskitic structure.

Epitaxy per se is well known, cf. for example, I. Brodie and J.J. Murray, The Physics of Microfabrication, Plenum Press, New York and London, 1982, pp. 16 ff. The term epitaxy describes a deposition process whereby a single-crystal material is applied to a substrate having the same crystal orientation. In order for the depositing material to atomically interface with the substrate surface, two important conditions must be met: Firstly, the substrate surface must present to the depositing material a suitable number of nucleation sites where deposited atoms give up some energy and bond to the surface atoms; and secondly, the lattice match of the surface relative to the depositing material must be a maximum.

The epitaxy process is performed in a reactor chamber, usually at elevated temperatures and in an atmosphere with specially controlled pressure, or in vacuo. Depending on the mechanism by which the depositing material is replenished in the reactor chamber, one distinguishes between three types of epitaxy processes, viz. vapor-phase epitaxy (VPE), liquid-phase epitaxy (LPE), and molecular beam epitaxy (MBE).

In the vapor-phase epitaxy process, a gas stream containing the material to be deposited is caused to

flow over the heated substrates. The growth rate of the epitaxial layer can be made a function of the concentration in the gas stream of the material to be deposited.

One example of a prior reference to vapor-phase epitaxy is US-A-4,058,430 which discloses a method for growing highly oriented compound thin films on a substrate by subjecting the substrate to the vapor of a first single element which can react with the substrate surface at a temperature sufficiently high for the reaction to occur, to form a single atomic layer of the first single element on the surface, and then subjecting the thus formed new surface to the vapor of a second single element which can react with the first single element at a temperature sufficiently high for the reaction to occur, so as to form a single atomic layer of the second single element on the surface of the first single element. This procedure is repeated until the compound film reaches the desired thickness.

In the liquid-phase epitaxy process, the material to be deposited is retained in a solution holder at elevated temperature, and is brought in contact with the substrate as holder and substrate are mutually displaced. With a plurality of solution holders in a row, it is possible to deposit multilayers of different materials onto the same substrate.

Liquid-phase epitaxy was, for example, described by H. Nelson, "Epitaxial growth from the liquid state and its applications to the fabrication of tunnel and laser diodes", RCA Rev. 24 (1963) p.603. Nelson used a tipping system, where the substrate and the epitaxial solution are placed at opposite ends of a graphite boat which in turn is arranged inside a growth tube containing a high-purity atmosphere. The tube is situated in a furnace that can be tipped to elevate either end of the boat. The solution used consists of gallium and gallium arsenide in such amounts that saturation occurs at the growth temperature.

The third type of epitaxy process, the molecular beam epitaxy, achieves crystal growth in an ultra-high vacuum environment through the reaction of multiple molecular beams with the heated substrate. The molecular beam sources each consist of a furnace containing one of the constituent elements of the deposit in a crucible. The furnaces are arranged so that the central portion of the beam flux distribution intersects the substrate. Shutters arranged on each of the furnaces permit the controlled initiation or cessation of the respective beam fluxes.

One example for the great volume of literature on molecular beam epitaxy is K. Ploog, "Molecular Beam Epitaxy of III-IV compounds, *Crystals: Growth, Properties and Applications*, ed. L.F. Boschke, Heidelberg, Springer-Verlag (1979).

For the purposes of the present invention, advanced techniques of the three basic epitaxy processes are employed, such as metal-organic vapor-phase epitaxy (MOVPE) or chemical beam epitaxy (CBE), to grow very abrupt interfaces and, at the same time, allow the deposited layers to be very thin through precise control of the growth parameters.

The paper "Single Crystal Superconducting  $Y_1Ba_2Cu_3O_{7-x}$  Oxide Films By Molecular Beam Epitaxy" by J. Kwo, M. Hong, R.M. Fleming, T.C. Hsieh, S.H. Liou, and B.A. Davidson, published in Conference Proceedings "Novel Mechanisms of Superconductivity" June 22 through 26, 1987, Berkely, CA., describes a method for preparing single-crystal  $Y_1Ba_2Cu_3O_{7-x}$  films by thermally coevaporating the constituents of the films from three separate sources simultaneously onto the (100) face of  $SrTiO_3$ . The films produced with this method are amorphous and have a reported thickness of about 900 nm.

Another reference dealing with "thick" films (about 1  $\mu m$ ) is C. Webb et al., "Growth of high- $T_c$  superconducting films using molecular beam epitaxy techniques", Appl. Phys. Lett. 51 (15) 1987, pp. 1191-1193. The high- $T_c$  superconductor reported in this reference is  $DyBa_2Cu_3O_{7-x}$  which has been grown onto a  $SrTiO_3$  substrate. However, in this case, as well as in the above-mentioned Kwo et al. reference, the films required oxidation at elevated temperatures as a post-anneal process in order for them to become superconducting.

The present invention is, however, not directed to such thick films but rather to the formation of monolayer films, i.e. films comprising only one or very few molecular layers of a superconducting material. Of relevance in this connection is a paper by M.A. Tischler and S.M. Bedair, "Growth and Characterization of Compound Semiconductors by Atomic Layer Epitaxy", Journal of Crystal Growth 77 (1986) pp. 89-94. As described in this reference, growth proceeds by the sequential deposition of individual layers of atoms of the elements making up the final compound. For example, gallium arsenide is grown by first depositing an atomic layer of gallium and then an atomic layer of arsenic. The cycle is repeated until the desired thickness is achieved. The first atomic layer is chemically adsorbed at the substrate surface, any following atoms are only weakly bonded and tend to re-evaporate. This is a self-limiting mechanism which prevents the deposition of more than one monolayer at a time. The second-material atomic layer finds a fresh surface and again, one monolayer of atoms gets adsorbed to that new surface. If the operational parameters are appropriate, a chemical reaction will cause the atomic monolayers to form a monomolecular layer of the desired compound.

While in the Tischler-Bedair proposal cited above the new compound is generated from pure elements, in a proposal by H. Watanabe and A. Usui "Atomic Layer Epitaxy", Inst. Phys. Conf. Ser. No. 83: Chapter I, Paper presented at Int. Symp. GaAs and Related Compounds, Las Vegas, Nevada, 1986, the starting materials are metal halogenides or metalorganic compounds, such as GaCl and Ga(CH<sub>3</sub>)<sub>3</sub>, and arsine AsH<sub>3</sub>.

All of the references cited above, while dealing with thin film epitaxy, do not relate to the formation of the crystallographic structure of the superconducting compound synthesized, except that, of course, some of them mention that the superconducting phase must have a layered structure of the K<sub>2</sub>NiF<sub>4</sub> type.

In contrast, it is an object of the present invention to propose a method for making high-T<sub>c</sub> superconductors having a predetermined crystallographic structure. This object is achieved by epitaxially growing sequences of atomic layers of the elements constituting the desired superconductor compound onto surfaces having a crystallographic structure at least similar to the structure of the compound being made. The superconductor structure finally achieved can comprise from one single monomolecular layer to a plurality of monomolecular layers which may make up a sandwich structure. The layers may be stacked in regular or non-regular sequences not possible in natural crystals. The non-regular sequence, in particular, may be grown in a fractal way. The fractals are determined mathematically.

Details of the invention will hereafter be described with respect to some examples of artificial high-T<sub>c</sub> superconductor materials, with reference to the attached drawings in which:

Fig. 1 shows the crystal lattice of strontium titanate SrTiO<sub>3</sub>;

Fig. 2 illustrates the crystal structure of artificial La<sub>2</sub>CuTiO<sub>6</sub>;

Fig. 3 depicts the crystal structure of artificial La<sub>2</sub>Cu(Al<sub>1/2</sub>, Zr<sub>1/2</sub>)O<sub>6</sub>;

Fig. 4 shows the lattice structure of artificial Sr<sub>2</sub>LaCu<sub>2</sub>WO<sub>8</sub>;

Fig. 5 shows the crystal structure of the orthorhombic form of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub>;

Fig. 6 is a schematic representation of epitaxy apparatus suited to create the artificial superconductor compounds in accordance with the invention.

One material particularly suited as a substrate in the epitaxial growth of high-T<sub>c</sub> superconductor material is strontium titanate SrTiO<sub>3</sub>, which forms crystals like perovskite (Fig. 1). Each titanium ion 1 is octahedrally surrounded by six oxygen ions 2; the bigger strontium ions 3 being disposed in the spaces in between. At room temperature, SrTiO<sub>3</sub> is cubic with a small unit cell, and paraelectric. At about 100 K, SrTiO<sub>3</sub> starts to undergo a cubic-tetragonal phase transition with a non-ferroelectric phase, because this phase is more favorable energetically.

Another material suitable as a substrate is zirconium dioxide ZrO<sub>2</sub>. This material can even be coated over polycrystalline silicon bulk material, in order to minimize any mismatches in lattice constants.

Still another promising material is zinc selenide Zn<sub>1-x</sub>Se<sub>x</sub>. By varying x, the lattice constant of this compound can be adjusted within certain borders, so as to render it essentially equal to the lattice constant of the high-T<sub>c</sub> superconductor material to be grown.

Other examples of materials suitable as a substrate for the growth of high-T<sub>c</sub> superconductor materials include barium fluoride BaF<sub>2</sub>, and II/VI compounds such as zinc telluride Zn<sub>1-x</sub>Te<sub>x</sub>, cadmium selenide Cd<sub>1-x</sub>Se<sub>x</sub>, and cadmium telluride Cd<sub>1-x</sub>Te<sub>x</sub>.

Returning to the manufacturing of artificial high-T<sub>c</sub> superconductor materials, it has been found that one essential feature is the layered structure of the superconducting metal oxides. The monolayer epitaxy allows for the generation of such layers and for a systematic variation of the layer sequences and, most important, of the crystalline structure of those layers. Figs. 2, 3, and 4 show examples of layered perovskite high-T<sub>c</sub> superconductors that can be grown with single-valence or mixed-valence copper oxide layers separated by non-superconducting metal oxide layers.

Another essential feature of high-T<sub>c</sub> perovskite copper oxide superconductors is the antiferromagnetic character of the non-conducting (i.e. undoped) oxide at low temperatures. The antiferromagnetic behavior is characterized by a state in which neighboring spins are antiparallel, instead of parallel. Accordingly, the non-conducting copper oxide exhibits a paramagnetism with low positive susceptibility that varies with temperature.

Fig. 2 is a representation of a crystal lattice of an artificial high-T<sub>c</sub> superconductor compound manufactured in accordance with the present invention. The compound is La<sub>2</sub>CuTiO<sub>6</sub>. Its crystal structure is of the ABB' type and consists of a layer sequence comprising a (B) copper oxide layer 4, a (B') titanium oxide layer 5, and interstacked (A) lanthanum oxide layers 6. The copper oxide and titanium oxide layers 4 and 5, respectively, consist of octahedra having metal atoms in their centers and shared oxygen atoms at their corners. The spaces between every four octahedra house one lanthanum atom 6 each. This crystal structure is grown on top of a SrTiO<sub>3</sub> crystal 7 which has essentially the same lattice constant as the desired superconductor material.

Fig.3 shows an example of an ABB' structure of  $\text{La}_2\text{Cu}(\text{Al}_{1/2}, \text{Zr}_{1/2})\text{O}_6$ . The layer sequence consists of a mixed (B')  $\text{Al}^{3+}/\text{Zr}^{4+}$  oxide layer 8, a (A) lanthanum oxide layer 9 and a (B) mixed-valence  $\text{Cu}^{2+}/\text{Cu}^{3+}$  oxide layer 10. This lattice is grown on top of a  $\text{SrTiO}_3$  crystal 11 with an interstacked lanthanum layer 12.

While the manufacture of one-constituent oxide layers is straightforward, the creation of oxide layers of the mixed  $\text{Al}^{3+}/\text{Zr}^{4+}$  type requires the simultaneous presence of Al and Zr in a 1:1 relationship, preferably in the form of gaseous organic compounds of these metals. Examples for organic compounds of interest in this connection are aluminium alkoxide  $\text{Al}(\text{OCH}_3)_3$  and zirconium cyclopentadienyl  $\text{Zr}(\text{OC}_2\text{H}_5)_2$ .

Generally, the following types of metalorganic compounds may find use in connection with the present invention:

Type	Example	Name
Halogenides	$\text{YCl}_3$	Yttrium chloride
Alkyls	$(\text{CH}_3)_3\text{La}$	Methylanthanum
Alkoxides	$\text{Ba}(\text{OCH}_3)_2$	Methoxybarium
Acetylacetonates	$\text{Ba}[\text{OC}(\text{CH}_3)_2\text{CHCO}(\text{CH}_3)_2]$	Barium acetylacetonate
Cyclopentadienyls	$(\text{C}_5\text{H}_5)_2\text{Ba}$	Barium cyclopentadienyl
Carbonyls	$\text{C}_5\text{H}_5\text{Mn}(\text{CO})_3$	Manganese cyclopentadienyl Carbonyl

An example of a crystal structure of the AA'BB' type is shown in Fig.4. The superconductor material is  $\text{Sr}_2\text{LaCu}_2\text{WO}_3$ . The layer sequence consists of mixed (B)  $\text{Cu}^{2.5+}$  and (B')  $\text{W}^{6+}$  oxide layers 13 and 14, respectively, separated alternatively by (A)  $\text{Sr}_2^{2+}$  and (A')  $\text{La}^{3+}$  oxide layers 15 and 16, respectively. Again, the crystal lattice rests on top of a  $\text{SrTiO}_3$  crystal 17 with an interstacked lanthanum layer 16'.

Fig.5 shows another artificial superconductor compound in its orthorhombic form, viz.  $\text{YBa}_2\text{Cu}_3\text{O}_7$ . In contrast to the cubic perovskite structure with only corner-shared octahedra, in the compound of Fig.5, corner-sharing square pyramid copper oxide layers 18 and 19 arranged opposite each other form rhombic spaces in which first and second layers 20, 20' of barium atoms 21 (forming barium oxide  $\text{BaO}$ ) are disposed, separated by at least one other copper oxide layer 22 consisting of ribbons of square-planar  $\text{CuO}_4$  polyhedra. Neighboring layers 18 and 19, respectively, comprising the pyramid shaped copper oxide are joined by interstacked planar layers 23 of yttrium oxide.

It has been found (T. Schneider and D. Baeriswil, Critical Temperature of High- $T_c$  Superconductors, Zeitschrift für Physik A, -to be published) that the critical temperature  $T_c$  of superconductors of the type shown in Fig.5 is dependent on the number  $n$  of interstacked copper oxide layers,  $T_c = f(n)$ . This provides for the possibility of "engineering" the superconductor compounds so as to adapt their critical temperature to the needs of the particular circumstances by choosing the appropriate number of layers. Accordingly, in the compound shown in Fig.5, more planar  $\text{CuO}_4$  layers 22 may be added.

Having described some examples of artificial high- $T_c$  superconductors, the description will now turn to the apparatus for growing epitaxial layers. This is basically a sophisticated extension of vacuum evaporation apparatus comprising a multichamber vessel 25 having a fast entry load-lock 26, a preparation chamber 27 and a growth chamber 28. A typical setup is illustrated in Fig.6. Vessel 25 can be pumped to ultra-high vacuum conditions (about  $10^{-9}$  Pa) using a suitable combination of ion, cryo-, turbomolecular, diffusion, sorption and sublimation pumps 29. The use of UHV conditions enables the incorporation of high-vacuum based surface analytical and diagnostic techniques. For example, reflection high-energy electron diffraction (RHEED) apparatus 30 may be employed to examine the substrate prior to, and the actual epitaxial film during deposition. A mass spectrometer 31 may be provided for monitoring the gas composition in growth chamber 28 and for detecting possible leaks. Other surface analysis instruments, such as an Auger electron spectroscope 32, may be placed in preparation chamber 27 to reduce contamination problems.

The monocrystalline substrate 33 is arranged on a trolley 34 which enables it to be moved between load-lock 26 and growth chamber 28, passing preparation chamber 27. Substrate 33 may be heated by a heating coil 35. Facing substrate 33 are a number of sources 36 through 40 from which different materials can be emitted in the epitaxy process. These individually shuttered sources may encompass, for example, evaporators heated resistively or by electron beam, or sources for metals in the form of metal-organic compounds, or gas sources for performing dielectric, metal or metal oxide depositions. In addition, several gas inlets 41 through 44 are provided for introducing controlled amounts of known gases.

Substrate 33 is preferably oriented in vertical direction to facilitate the deposition of materials from the beams emitted from sources 36 through 40. To maintain a constant distance of sources 36 through 40 from substrate 33, the sources may be arranged on a remote-controlled arcuate (or straight) slider 45.

In operation, after the monocrystalline substrate 33 is placed on trolley 34 and introduced into vessel



25, load-lock 26 is closed. After pumping to UHV conditions, substrate 33 is brought into position for deposition. The appropriate one of sources 36 through 40 is placed opposite substrate 33. After substrate 33 has reached its operative temperature, the shutters of the first set of sources are opened, and/or the appropriate gas inlet(s) is operated, for a predetermined period of time. The first part of the epitaxy cycle is completed when a monoatomic or monomolecular layer of the first constituent has settled on the substrate.

The second part of the epitaxy cycle is started as soon as there is no residue left in the vacuum of the preceding source material. Then the second set of sources is activated for the appropriate period of time so as to permit the second source material to react with the first source material as determined by the stoichiometry of the materials in question.

This procedure is repeated for all individual constituents the deposit is finally to contain, and the entire cycle is repeated for each additionally desired layer of the superconductor material.

Over any other methods for the creation of chemical compounds, the monolayer epitaxy process has the advantage that it permits the formation of artificial compounds, i.e. those that do not exist in nature, on top of seed crystals having essentially the same lattice structure as the compounds desired. This is in contrast to other deposition methods by which only polycrystalline, or bulk materials can be obtained. In view of the fact that layered structure is an essential feature of all high- $T_c$  superconductors, the inventive method is of great importance in the manufacture of these superconductors.

## 20 Claims

1. Method for making artificial, layered high- $T_c$  superconductor compounds by monolayer epitaxy, characterized by the following steps:

- placing a monocrystalline substrate (7, 11, 17, 33) of a material from the group comprising strontium titanate  $\text{SrTiO}_3$ , zirconium dioxide  $\text{ZrO}_2$ , zinc telluride  $\text{Zn}_{1-x}\text{Te}_x$ , zinc selenide  $\text{Zn}_{1-x}\text{Se}_x$ ,  $\text{BaF}_2$ , cadmium selenide  $\text{Cd}_{1-x}\text{Se}_x$  and cadmium telluride  $\text{Cd}_{1-x}\text{Te}_x$ , wherein  $x < 1$ , in an UHV chamber (27, 28) having a plurality of independent sources (36...40) for materials for epitaxial deposition,
- exposing said substrate (7, 11, 17, 33) in a predetermined sequence to as many different ones of said sources (36...40) of constituent materials as the superconductor compounds being made should contain,
- activating said sources (36...40) in accordance with a predetermined pattern of activity, said pattern involving
  - data determining which particular constituent material is to be deposited at any one time;
  - data relating to the amount and concentration of the particular constituent material to be emitted from the activated source (36...40)
  - data relating to the period of time the exposure of said substrate (7, 11, 17, 33) to the individual constituent materials should last for one monoatomic/monomolecular layer of the particular constituent material to settle on the current substrate surface;
  - data relating to the operating temperature at which the exposure is to be performed, said data including information on the operating temperature of the current substrate surface, on the operating temperature of the source (36...40) of the particular constituent material, and on the reaction temperature required for the desired high- $T_c$  superconductor material to form in accordance with a particular, desired crystal structure;
- repeating the preceding steps as often as corresponds to the number of monomolecular/monoatomic layers the final superconductor compound should contain;
- cooling the resulting crystal to ambient temperature and removing it from the UHV chamber (27, 28).

2. Method in accordance with claim 1, characterized in that the epitaxial deposition of at least part of said constituent materials is made from a gas phase.

3. Method in accordance with claim 1, characterized in that said gas phase contains the metal atoms to be deposited in the form of an organic compound of the particular metal.

4. Method in accordance with claim 1, characterized in that the epitaxial deposition of said constituent materials is made from at least one molecular beam of the particular material(s).

5. Method in accordance with claim 1, characterized in that said monocrystalline substrate (7) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (6) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said strontium titanate substrate (7), that in a second epitaxial operation a layer (4) of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said lanthanum oxide monolayer (6), that in a third epitaxial operation a second monolayer (6') of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said cuprous oxide layer (4), that in a fourth epitaxial operation a monolayer (5) of octahedral titanium dioxide  $\text{TiO}_2$  is deposited onto said second lanthanum oxide monolayer (6'), the four individual epitaxial

operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{La}_2\text{CuTiO}_6$  crystal to be stoichiometrically correct and to assume a layered, octahedral structure of the ABB' type.

6. Method in accordance with claim 5, characterized in that said sequence of four epitaxial deposition operations is repeated as many times as the desired thickness of the resulting superconductor compound requires.

7. Method in accordance with claim 1, characterized in that said monocrystalline substrate (11) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a monomolecular layer (12) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said substrate (11), that in a second epitaxial operation a monolayer (8) of mixed aluminium oxide  $\text{Al}_2\text{O}_3$  and zirconium oxide  $\text{Zr}^{4+}\text{O}_2$  is deposited onto said layer (12) of lanthanum oxide, that in a third epitaxial operation a second layer (9) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said monolayer of mixed oxides, and that in a fourth epitaxial operation octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second monolayer (9) of lanthanum oxide, the four individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{La}_2\text{Cu}(\text{Al}_{1/2}, \text{Zr}_{1/2})\text{O}_6$  crystal to be stoichiometrically correct and to assume a layered, octahedral structure of the ABB' type.

8. Method in accordance with claim 1, characterized in that said monocrystalline substrate (17) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (16') of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said monocrystalline substrate (17), that in a second epitaxial operation a first monomolecular layer (13) of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said lanthanum oxide layer (16'), that in a third epitaxial operation a first monomolecular layer (15) of strontium oxide  $\text{SrO}$  is deposited onto said monolayer (13) of cuprous oxide, that in a fourth epitaxial operation a first monomolecular layer (14) of tungstic oxide  $\text{WO}_3$  is deposited onto said first strontium oxide monolayer (15), that in a fifth epitaxial operation a second monomolecular layer (15') of strontium oxide  $\text{SrO}$  is deposited onto said monomolecular layer (14) of tungstic oxide, that in a sixth epitaxial operation a second monomolecular layer (13') of octahedral cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second strontium oxide layer (15'), and that in a seventh epitaxial operation a second monomolecular layer (16) of lanthanum oxide  $\text{La}_2\text{O}_3$  is deposited onto said cuprous oxide layer (13'), the seven individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature so as to permit the nascent  $\text{Sr}_2\text{LaCu}_2\text{WO}_9$  crystal structure of the AA'B type.

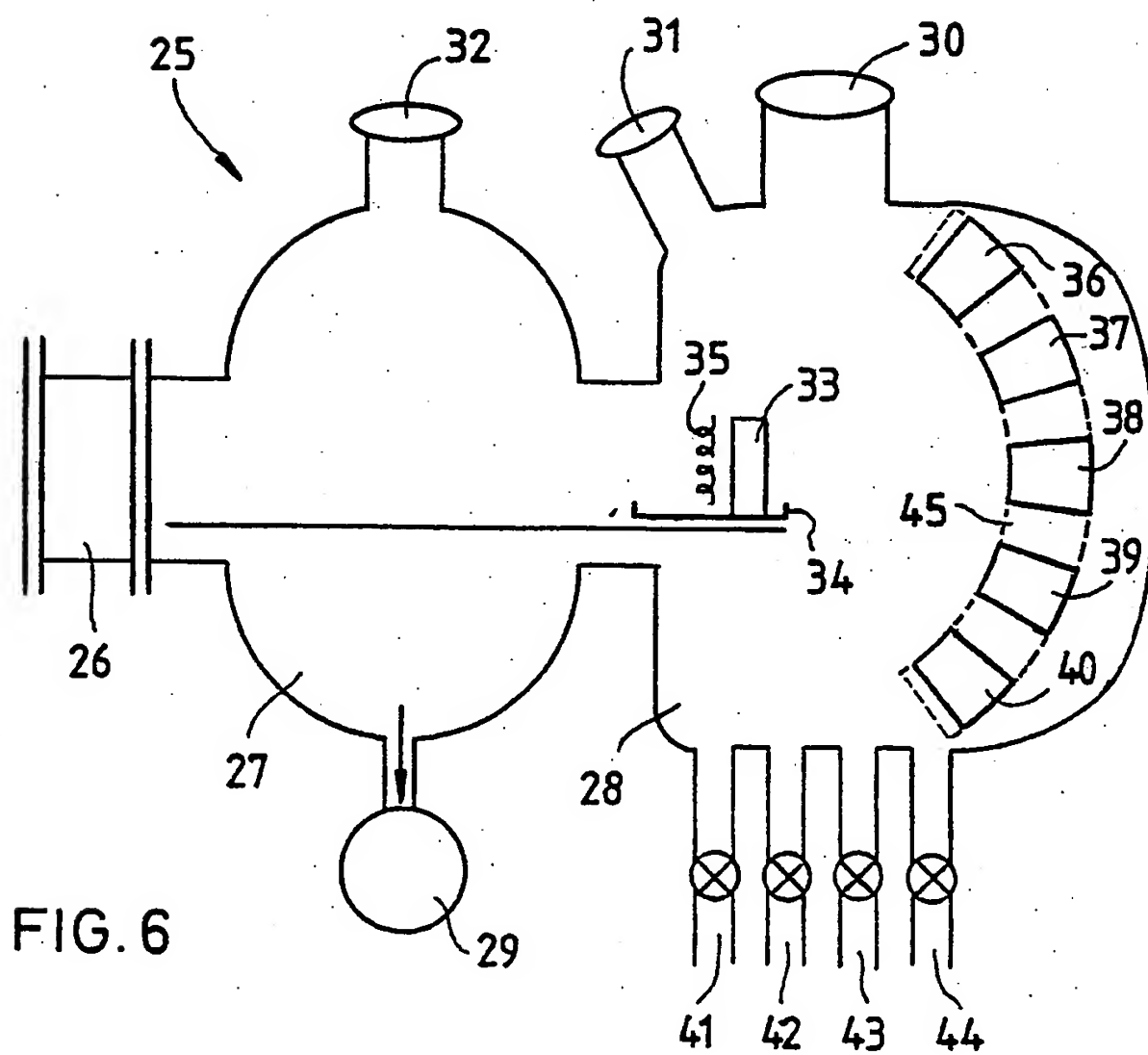
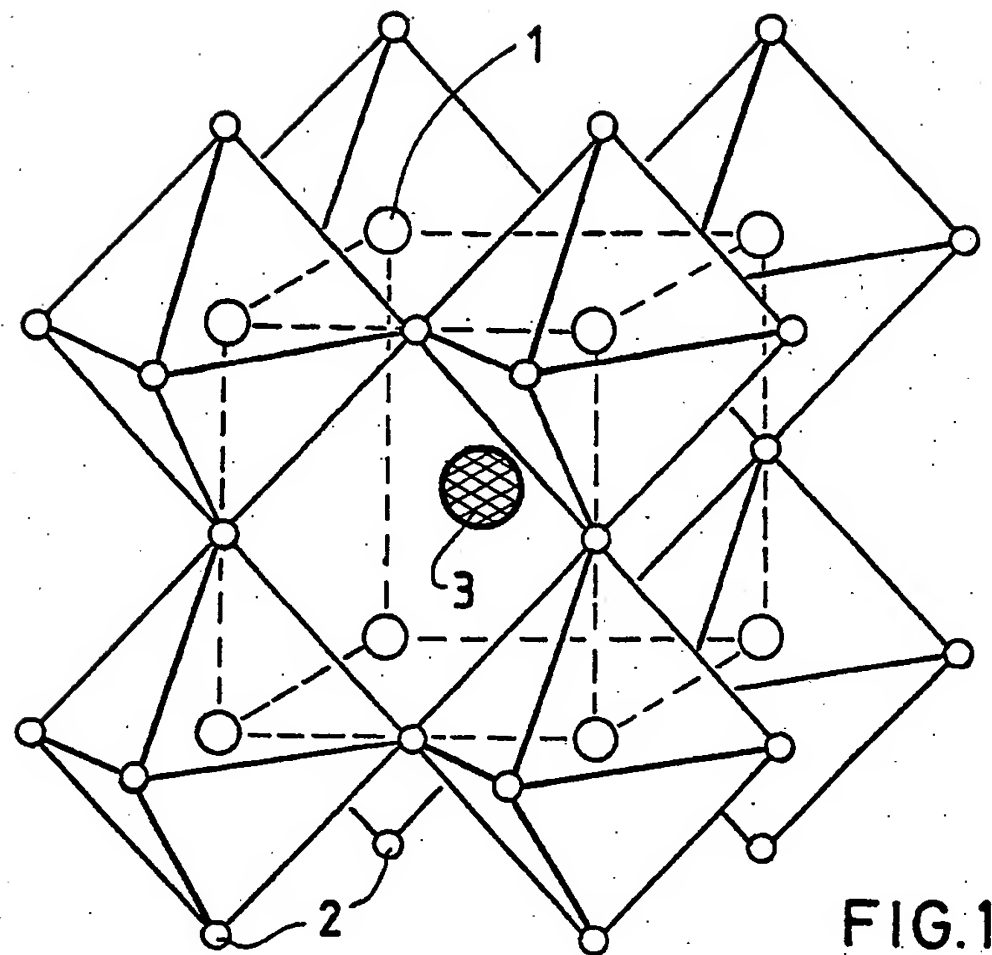
9. Method in accordance with claim 1, characterized in that said monocrystalline substrate (33) consists of octahedral strontium titanate  $\text{SrTiO}_3$ , that in a first epitaxial operation a first monomolecular layer (23) of yttrium oxide  $\text{Y}_2\text{O}_3$  is deposited onto said monocrystalline substrate (33), that in a second epitaxial operation a first monomolecular layer (19) of pyramidal cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said yttrium oxide layer (23), that in a third epitaxial operation a first monomolecular layer (20) of barium oxide  $\text{BaO}$  is deposited onto said monolayer (19) of cuprous oxide  $\text{Cu}_2\text{O}$ , that in a fourth epitaxial operation a layer (22) of ribbons of square planar copper oxide  $\text{CuO}_4$  polyhedra is deposited onto said barium oxide layer (20), that in a fifth epitaxial operation a second monomolecular layer (20') of barium oxide  $\text{BaO}$  is deposited onto said layer (22) of copper oxide polyhedra, that in a sixth epitaxial operation a second monomolecular layer (18) of pyramidal cuprous oxide  $\text{Cu}_2\text{O}$  is deposited onto said second barium oxide layer (20'), and that in a seventh epitaxial operation a second monomolecular layer (23) of yttrium oxide is deposited onto said cuprous oxide layer (18), the seven individual epitaxial operations being performed under controlled conditions regarding time of exposure, concentration of epitaxial source material, and reaction temperature, so as to permit the nascent  $\text{YBa}_2\text{Cu}_3\text{O}_7$  crystal to be stoichiometrically correct and to assume a layered, orthorhombic structure.

10. Method in accordance with claim 5, characterized in that said first and second monolayers (23) of yttrium oxide have a square planar structure.

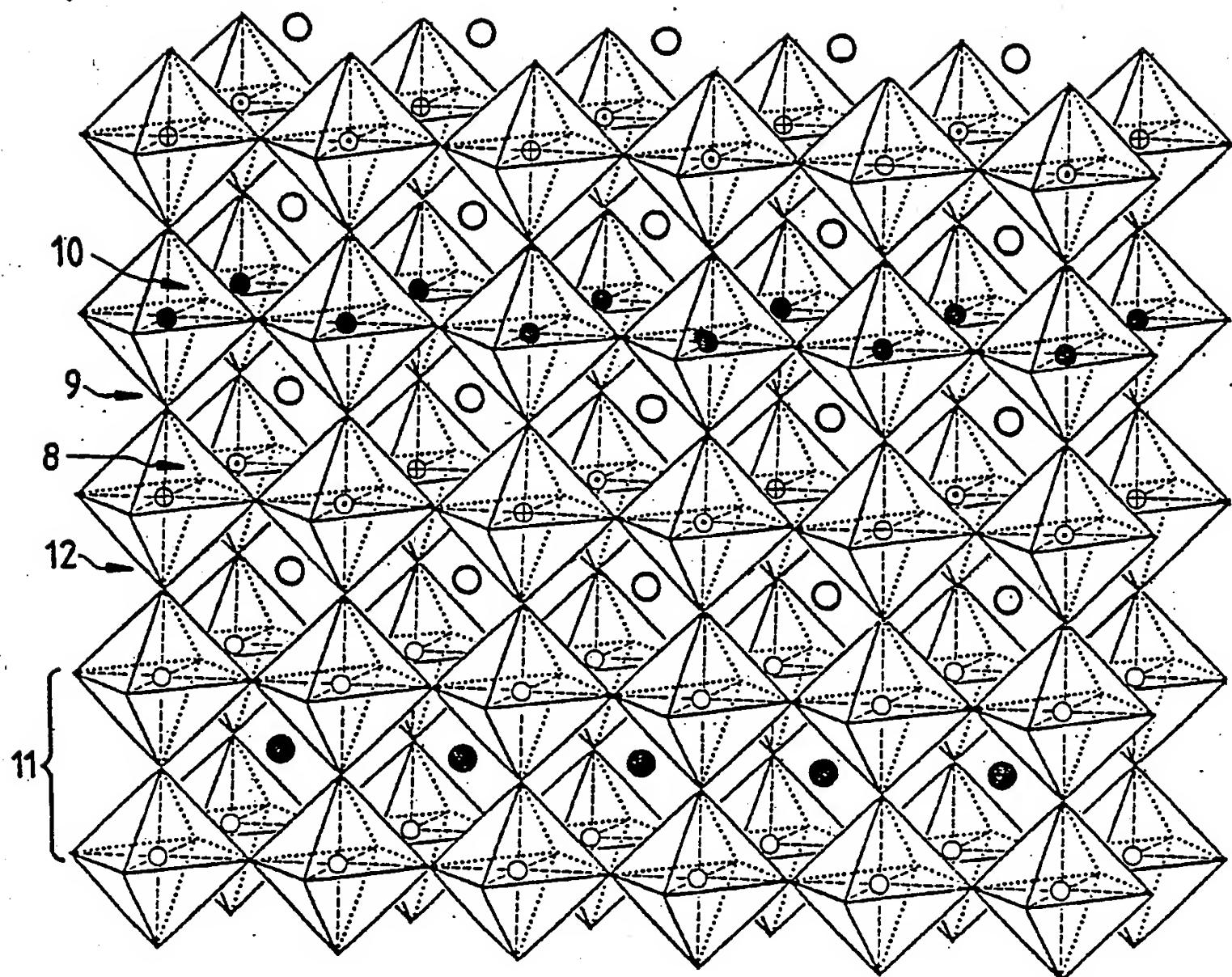
11. Method in accordance with claim 5, characterized in that said  $\text{YBa}_2\text{Cu}_3\text{O}_7$  crystal comprises at least two orthorhombic lattices consisting of  $\text{Ba}_2\text{Cu}_3\text{O}_5$  with an interstacked square planar yttrium oxide  $\text{Y}_2\text{O}_3$  layer (23).

12. Method in accordance with claim 5, characterized in that said cycle of seven epitaxial deposition steps is repeated as often as the desired thickness of the resulting layered structure requires.

13. Method in accordance with claim 5, characterized in that said fourth epitaxial deposition step in which a layer (22) of copper oxide  $\text{CuO}_4$  is deposited, is repeated at least once prior to continuing with the fifth step deposition so as to create a layered structure comprising more than one layer (22) of copper oxide  $\text{CuO}_4$  between consecutive layers (20, 20') of barium oxide  $\text{BaO}$ .







- Sr
- La
- $\text{Cu}^{2+}/\text{Cu}^{3+}$
- Ti
- ⊙ Al
- ⊕ Zr

FIG. 3



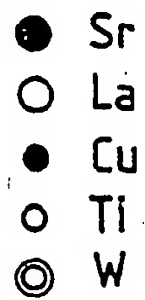
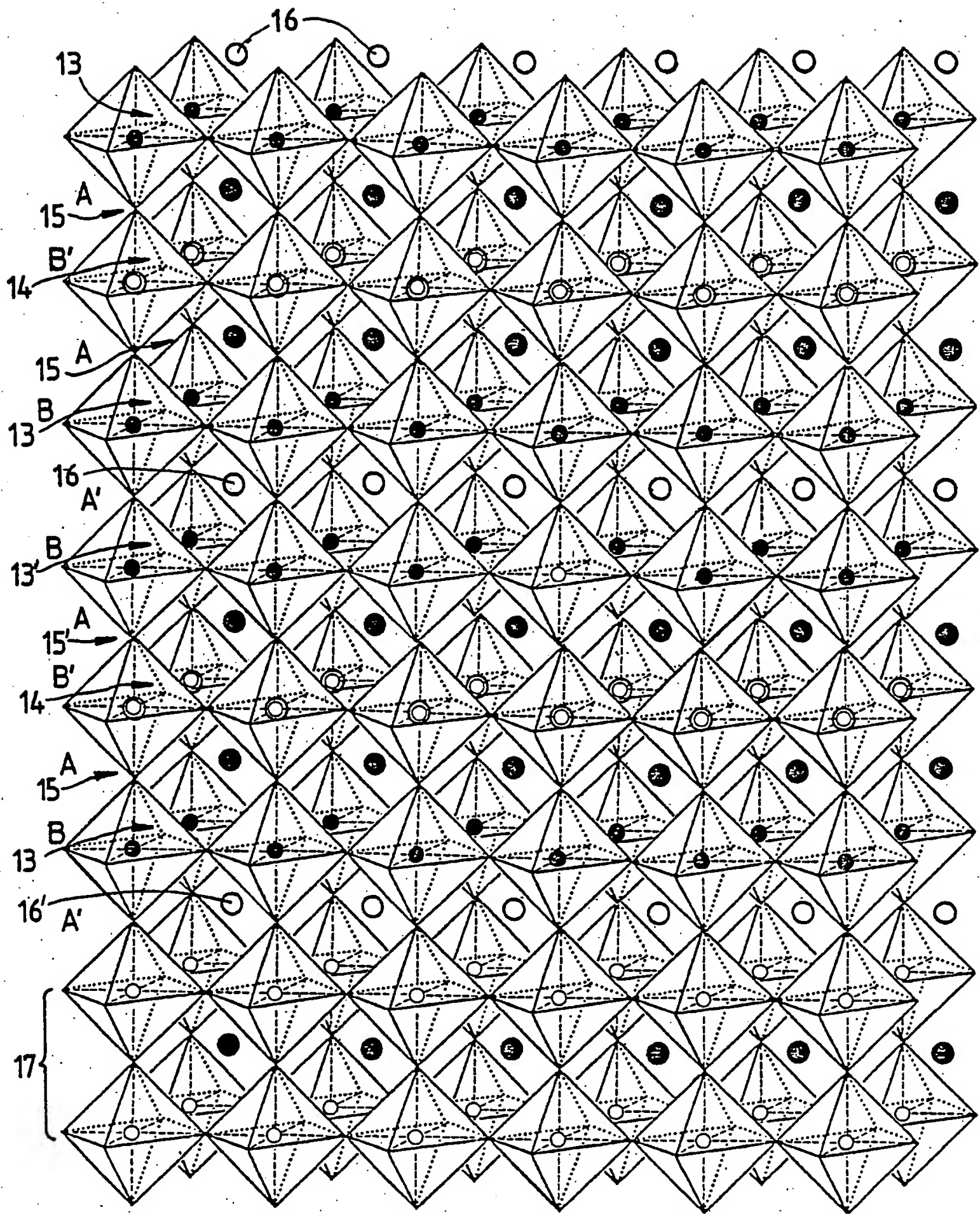
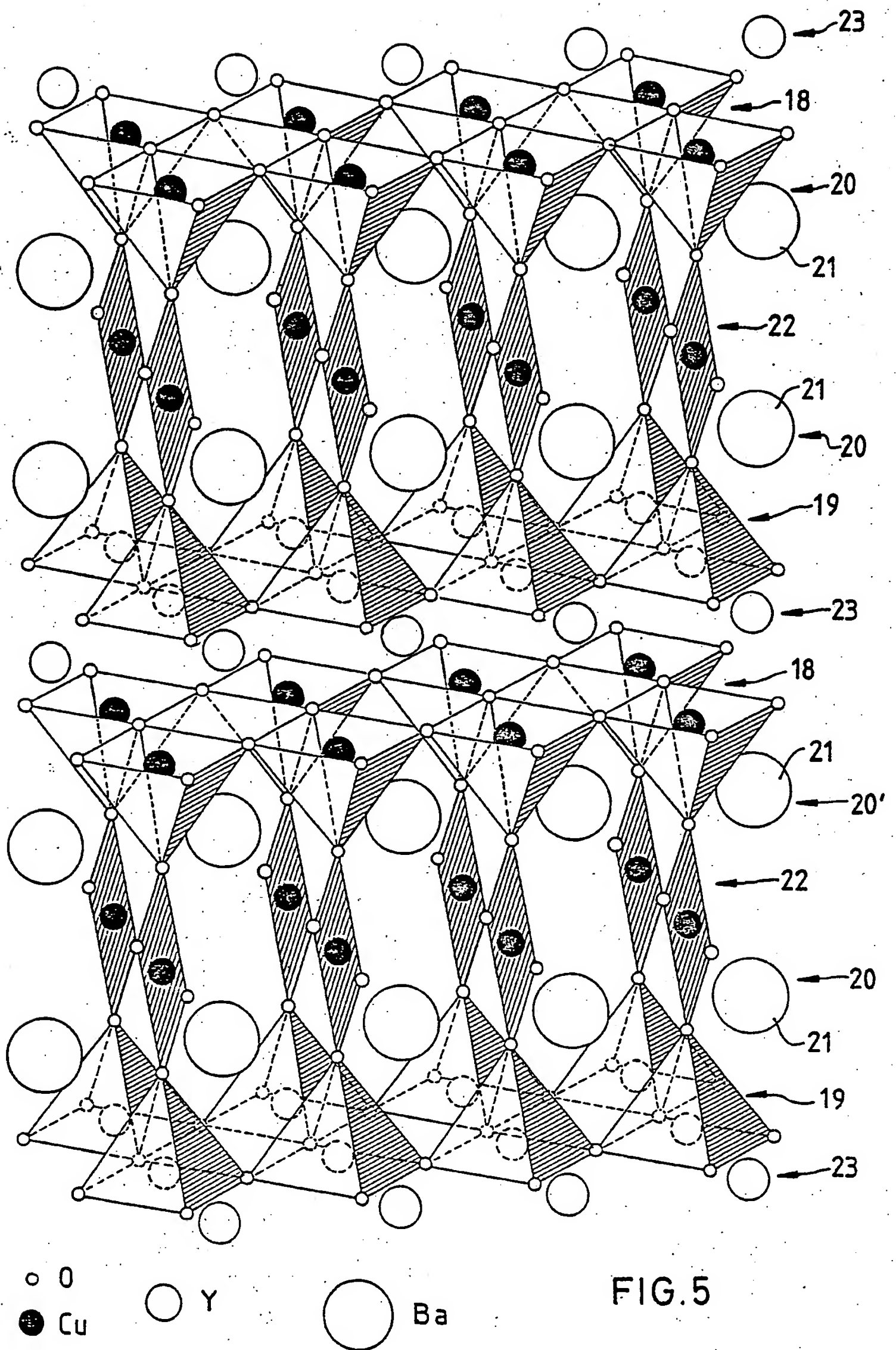


FIG.4





DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
X	AIP CONFERENCE PROCEEDINGS 1988, TOPICAL CONFERENCE ON THIN FILM PROCESSING AND CHARACTERIZATION OF HIGH TEMPERATURE SUPERCONDUCTORS, Anaheim, CA, 6th November 1987, no. 165, pages 122-129, American Institute of Physics, New York, US; Ph. HOUDY et al.: "Amorphization evidence from kinetic ellipsometry in monolayer-controlled deposition of RF sputtered YBaCuO compounds" * Paragraphs "Abstract, "Indtroduction", "Experimental set-up" - parts b,c; figures 5,7 *	1	H 01 L 39/24 H 01 L 39/12 C 30 B 29/22
Y	Idem	2-4	
A	Idem	9	
Y	APPLIED PHYSICS LETTERS, vol. 52, no. 20, 16th May 1988, pages 1743-1745, New York, US; A.D. BERRY et al.: "Formation of high Tc superconducting films by organometallic chemical vapor deposition" * Whole document *	2,3	TECHNICAL FIELDS SEARCHED (Int. Cl.4)  H 01 L
A	Idem	9	
Y	GB-A-2 162 862 (RESEARCH DEVELOPMENT CORP. OF JAPAN et al.) * Whole document *	2,3	
A	--- -/-	1	
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 02-02-1989	Examiner MORVAN D.L.D.
<div>CATEGORY OF CITED DOCUMENTS</div> <div>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</div> <div>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ..... &amp; : member of the same patent family, corresponding document</div>			



DOCUMENTS CONSIDERED TO BE RELEVANT															
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)												
D,Y	CONFERENCE PROCEEDINGS NOVEL MECHANISMS OF SUPERCONDUCTIVITY, Berkeley, CA, 22nd-26th June 1987, pages 699-703; J. KWO et al.: "Single crystal superconducting Y1Ba2Cu3O7-x oxide films by molecular beam epitaxy" * Whole document *	4													
D,A	Idem ---	9													
Y	THIN SOLID FILMS, vol. 57, no. 1, February 1979, pages 3-13, Elsevier Sequoia S.A., Lausanne, CH; A.C. GOSSARD: "GaAs/AlAs layered films" * Paragraph 2; figure 1 *	4													
A	Idem ---	1													
A	JAPANESE JOURNAL OF APPLIED PHYSICS, vol. 26, no. 9, September 1987, pages L1451-L1452; Y. SORIMACHI et al.: "Formation of superconducting Y-Ba-Cu-O thin films by the solid phase reaction between BaCO3/Cu/Y2O3 layers on single crystalline SrTiO3 substrate" * Whole document *	1,4,9													
A	GB-A-2 120 845 (OY LOHJA AB) * Whole document *	1,2,5,7													
A	PHYSICA STATUS SOLIDI (a), vol. 96, no. 1, July 1986, pages K79-K83, Akademie Verlag, Berlin, DE; O. PARKASH et al.: "Electrical properties of La2TiMO6 (M = Fe, Ni, Cu, and Zn)" * Page K80 * --- -/-	5	TECHNICAL FIELDS SEARCHED (Int. Cl.4)												
The present search report has been drawn up for all claims															
Place of search THE HAGUE		Date of completion of the search 02-02-1989	Examiner MORVAN D.L.D.												
<table border="0"><tr><td>CATEGORY OF CITED DOCUMENTS</td><td>T : theory or principle underlying the invention</td></tr><tr><td>X : particularly relevant if taken alone</td><td>E : earlier patent document, but published on, or after the filing date</td></tr><tr><td>Y : particularly relevant if combined with another document of the same category</td><td>D : document cited in the application</td></tr><tr><td>A : technological background</td><td>L : document cited for other reasons</td></tr><tr><td>O : non-written disclosure</td><td>.....</td></tr><tr><td>P : intermediate document</td><td>&amp; : member of the same patent family, corresponding document</td></tr></table>				CATEGORY OF CITED DOCUMENTS	T : theory or principle underlying the invention	X : particularly relevant if taken alone	E : earlier patent document, but published on, or after the filing date	Y : particularly relevant if combined with another document of the same category	D : document cited in the application	A : technological background	L : document cited for other reasons	O : non-written disclosure	.....	P : intermediate document	& : member of the same patent family, corresponding document
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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
E	DE-A-3 810 243 (HITACHI LTD) * Whole document * -----	1, 4	
			TECHNICAL FIELDS SEARCHED (Int. Cl. 4)
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 02-02-1989	Examiner MORVAN D.L.D.
<div>CATEGORY OF CITED DOCUMENTS</div> <div><div>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</div><div>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ..... &amp; : member of the same patent family, corresponding document</div></div>			



